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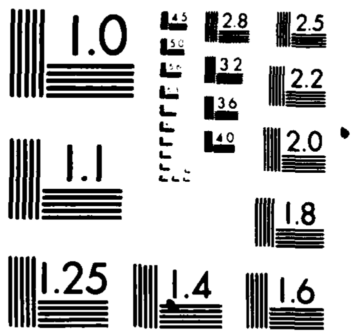

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PRELIMINARY ANALYSIS AND TEST RESULTS FOR CIRCUIT CARDS IN X-RAY AND GAMMA RAY ENVIRONMENTS

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Technical Report

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The measured response of typical circuit cards and simplified circuit cards to ionizing radiation is examined. As in previous tests, the response to the gamma rays is found to be reasonably well understood. The anomalous response to x-rays is again observed during and after biasing. For the simplified card, these amonalies are reasonably well understood; however, this is not true for cards with more complex geometries. Methods for understanding the response of the more complex cards are discussed.

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CONVERSION TABLE

MULTIPLY →	BY →	TO GET
TO GET ←	BY ←	DIVIDE

angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm^2	4.184 000 X E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 X E +1	*giga becquerel (GBq)
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	$t_K = (t°f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 X E -3	meter^3 (m^3)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 X E +3	kilo pascal (kPa)
ktap	1.000 000 X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N·m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 X E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 X E -2	kilogram-meter^2 (kg·m^2)
pound-mass/foot^3	1.601 846 X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 X E -2	**Gray (Gy)
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shake	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0° C)	1.333 22 X E -1	kilo pascal (kPa)

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION I
INTRODUCTION

Photons incident on systems penetrate walls creating free electrons within the materials and cavities of the system. The moving electrons, created by the photons or as replacement currents on the walls, generate electric and magnetic fields. This process is usually called an internal electromagnetic pulse (IEMP). As a result of these electromagnetic transients, IEMP can potentially damage the electric components within enclosures. This effect is present even though the box may be well shielded to the external electromagnetic fields. [1,2]

Combined with the IEMP is the interaction of this same radiation with the cables and circuit cards of the system. The radiation causes direct charge transfer between elements such as the lands, ground planes, interconnections and box walls. This process is called system generated EMP (SGEMP).[3-5]

In order to better understand the IEMP/SGEMP effects at the circuit card level, a number of analytical studies and experiments have been performed.[6-12] In this report, the results of two experiments are presented. Both generic and complex circuit cards were irradiated by the Modular Bremsstrahlung Source (MBS), and the Blackjack 3 (BJ3) source at Maxwell Laboratory. The MBS provides a low energy (<E>~24KeV) and low fluence spectrum. BJ3 provides a high energy (<E>~650KeV) and high fluence spectrum. The purpose of these experiments was to (1) verify and expand the data taken at a previous experiment at MBS where anomalous responses were observed, and (2) extend the data base to higher fluences that more nearly represent system specifications.

The first experiment at the MBS facility was designed to confirm and better characterize the anomalous response observed previously when real circuit cards were irradiated under various pressures and voltage biases. The response had been observed to change sign with bias, decrease from shot to shot, and return to its original value if set aside for several hours. Some of this behavior has been seen in cards [5, 8] and cables [3, 4] by other experimenters but has not been adequately explained.

The second test at the BJ3 facility was designed to measure the response at conditions of high fluence, 10 to 50 times that of the MBS. This serves two purposes. First is to provide a validation of models that are normally only valid at low fluences. The second is to provide data for better understanding of the anomalous effect. The card's response dependency on shot history can be partially explained by the trapping of charge within the dielectric. This charge can move under the influence of radiation creating a net dipole movement. This moment reduces the response in short periods (minutes) of time but will relax after long periods (hours). If this is true, the large movement of charge under high fluence should dominate the effect of the trapped charge, reducing or eliminating the time varying or anomalous response.

SECTION 2
CIRCUIT CARD IEMP/SGEMP MODELS

Detailed models of the card response have been thoroughly discussed in the previous report[3] and elsewhere[8] and will only be summarized here. Three mechanisms allow for the transfer of energy in the box IEMP coupling processes; direct transfer of charge, capacitive coupling, and inductive coupling. Direct transfer of charge is the movement of electrons through interaction with the photon environment. This transfer may be between surfaces such as wall to card, bulk currents within dielectrics, and a dipole layer formation within dielectrics from a storage or buildup of charge.

Energy is coupled between objects through the time rate of change of the electric fields. These varying fields cause currents to exist on conductive surfaces within the boxes. The current driven is proportional to the time derivative of the voltage created by the electric field and the capacitance defined by the geometry.

The time rate of change of the magnetic field inside a loop geometry will create an induced voltage around the loop. The magnitude is proportional to this $\dot{B}$ and the area of the loop.

Two other mechanisms have been shown to modify the response of the cards.[5] The first mechanism is a result of electrons trapped within the dielectric of the card.[8] This stored charge increases with each pulse until a plateau is achieved after a number of pulses. The number depends on the frequency of the shots. The card relaxes overnight.

The second mechanism is a result of circuit card bias. The pre-charged card attracts or repels secondary electrons resulting in an enhanced or reduced response depending on the sign of the bias.[5,9]

SECTION 3
MBS EXPERIMENTAL CONFIGURATION

Two complex and one generic circuit cards were tested at the MBS facility. The complex cards tested were the same Martin Marietta cards used in the previous experiment.[5] Each of the cards contained four conductive layers consisting of two signal planes, a ground plane, and a supply plane (Figure 1). The copper lands cover about 20% of the area of the face of the card. The actual dimensions of each card were 15 cm by 8.8 cm by 0.11 cm. Each card was mounted to an aluminum heat sink 0.32 cm thick. The two cards were mounted side by side for the test, one with the lands facing the MBS source and the other with the heat sink facing the source. Four measurements were taken for these cards. The response of the ground plane was measured directly by a scope (Figure 2). The response of the supply plane was either measured directly or through a 1 nf isolation capacitor. For some measurements bias was applied through a 100 Ω resistor. In addition, a 10 MΩ resistor to ground was installed to insure that free charge buildup on the supply plane was not the source of the anomalous measurements. The aluminum heat sink was also grounded to the aluminum box.

The other card was idealized or generic in that it consisted of only a supply plane, dielectric and a ground plane (Figure 3). The supply plane was directed towards the incoming radiation. Both planes were 1.4 mil solid copper (no lands). The same circuitry was attached to this card as the previous card (Figure 2). A second version of this card, covered by 0.25 cm of glyptol, was tested at MBS. The

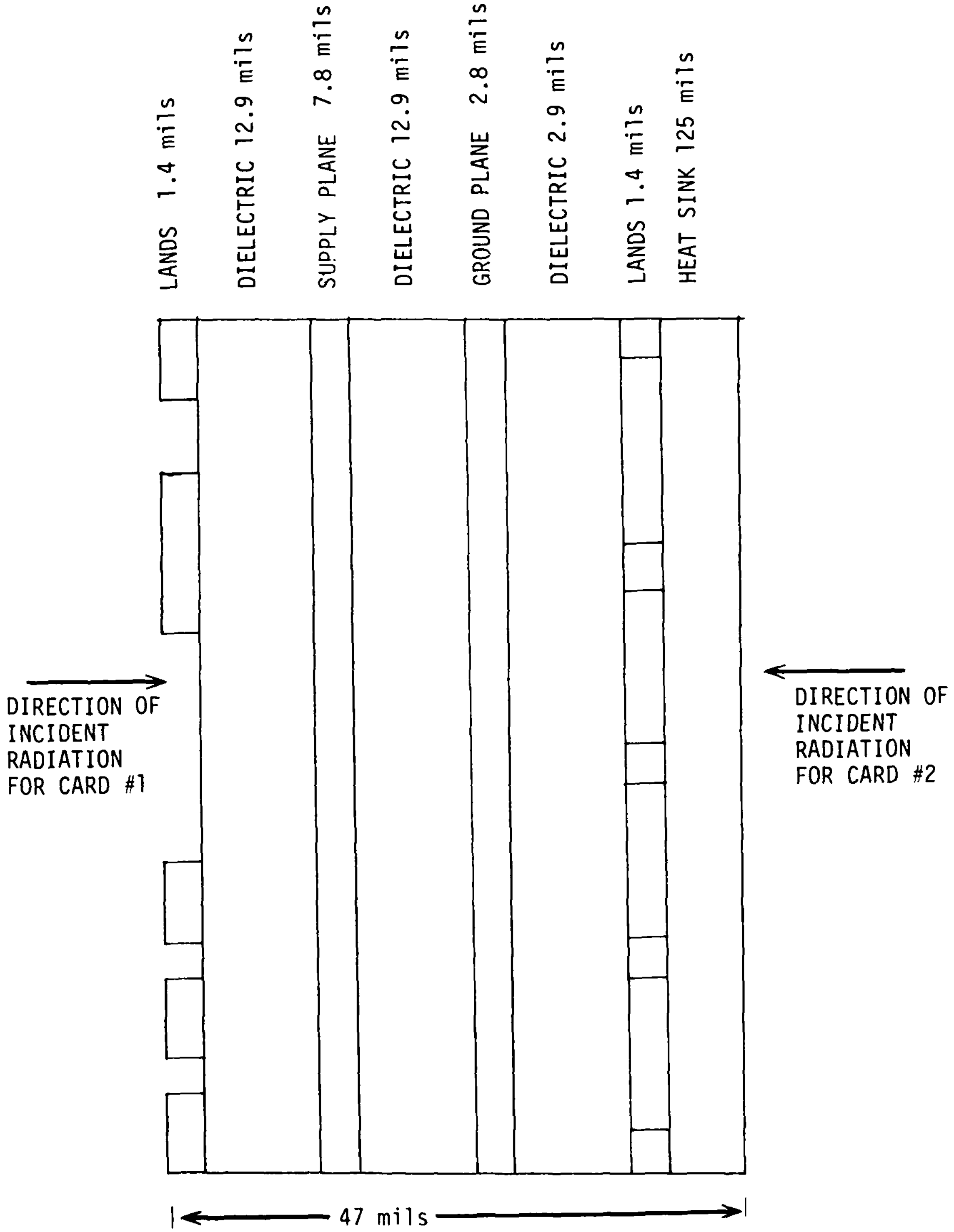


Figure 1. Cross sectional drawing of Martin Marietta Aerospace card

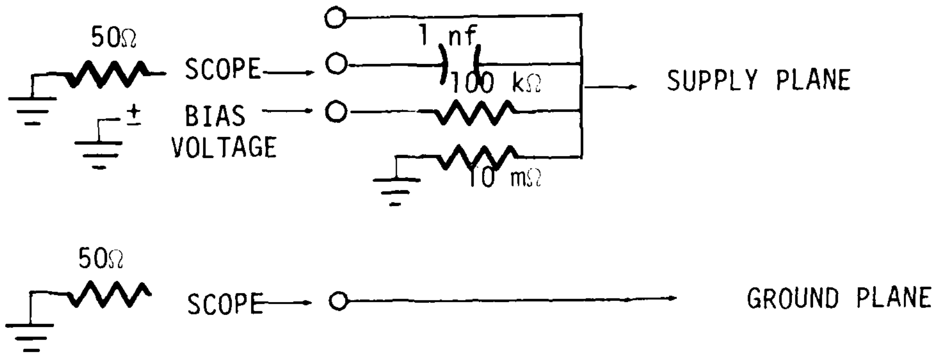


Figure 2. Schematic of experimental measurement circuits

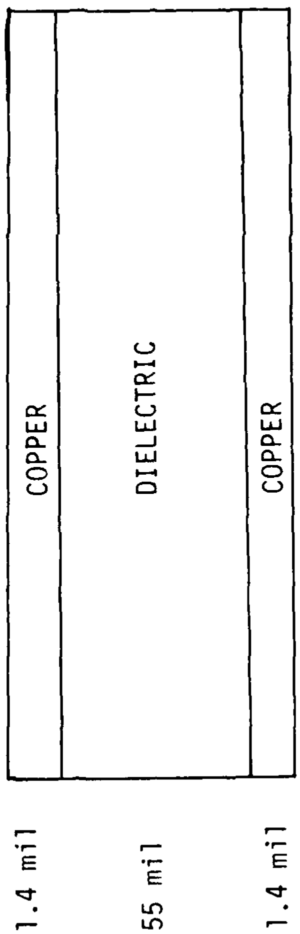


Figure 3. Cross sectional drawing of a generic card

glyptol represents a possible low Z carbon covering to reduce electron emission.

The circuitry inside the experimental cavity was shielded with mylar-covered lead. The signal lines were semi-rigid coaxial lines running to a screen room. The noise level was below a millivolt.

The low energy photon experiment was performed at the Modular Bremsstrahlung Source (MBS) facility at Maxwell Laboratories. The single module source provides an electron spectrum with a mean energy of 125 KeV that is converted to a low energy x-ray spectrum with an average energy of 25 KeV. This spectrum is characterized by the use of a flat response diode with a zero-to-peak rise time T1=14 nsec and a FWHM Γ = 21 nsec. The energy spectrum is shown in Figure 4.

The experiment was housed in an electromagnetically shielded aluminum box. This box was placed in an aluminum cylindrical vacuum chamber. The vacuum chamber resonates electromagnetically and contaminates the data with high frequency noise unless the experiment is adequately shielded by the second aluminum box.

Between the tantalon converter and the experiment were three filters. The first is a 105 mil mylar shield that acts as an electron catcher for the electrons produced by the MBS machine. The second and third filters were 1 mil aluminum foil that provide an RF cover for the canister and experiment box cover respectively. The filtered spectrum is shown as the second curve in Figure 4.

The energy spectra are scaled to the experiment by the use of the analysis of TLD dose measurements taken during the experiment. The dose per shot measured on the face of the

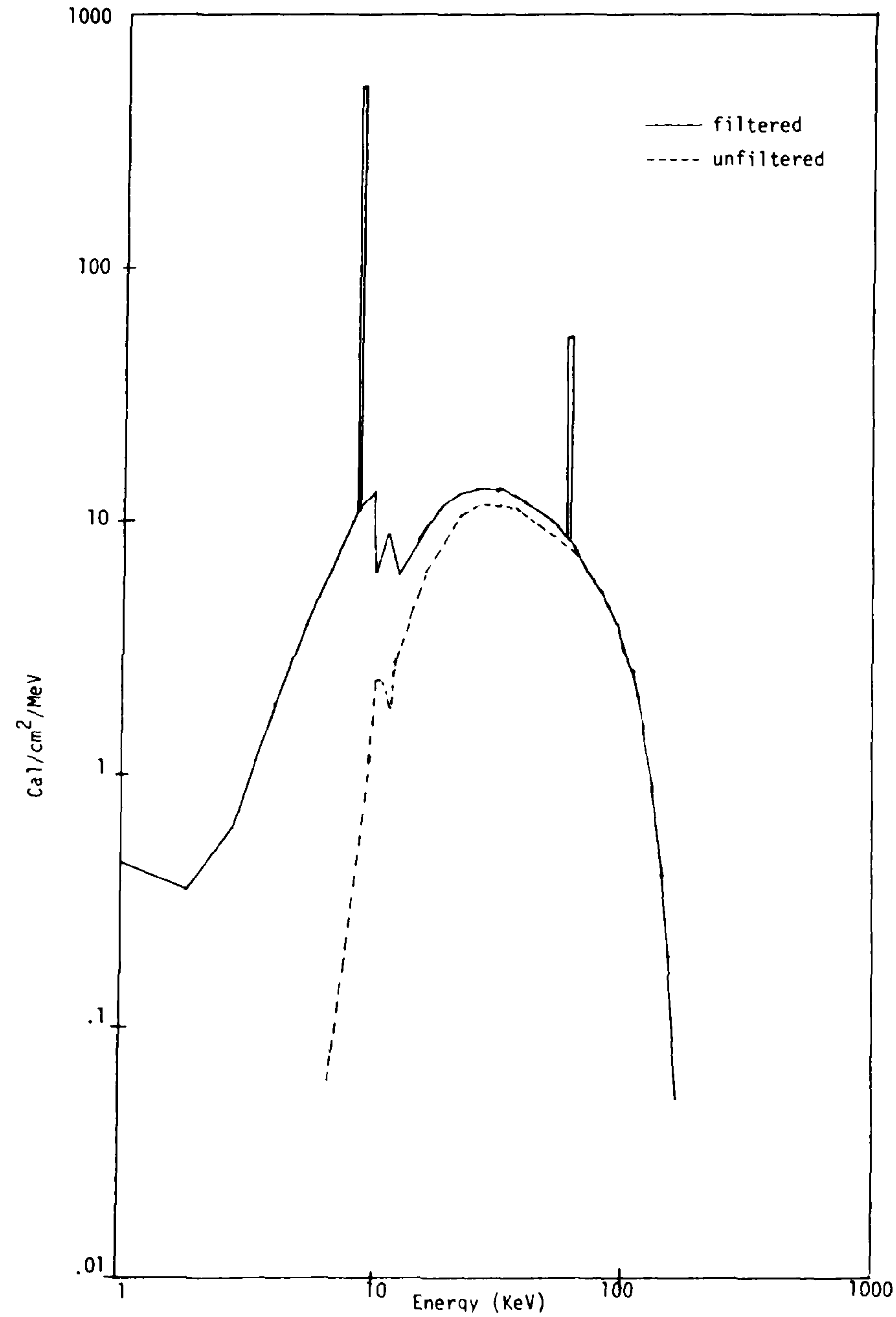


Figure 4. MBS spectra incident on box and circuit boards

cards was 126±23 Rad(Si) averaged over the face of the card. On the outside of the box, the average dose was 182 2±Rad(Si). These measurements of dose are in good agreement with analytical predictions of dose of 119 Rad(Si) and 184 Rad(Si), respectively, provided by Maxwell. This comparison gives confidence in using the measured dose to scale the transport calculations and to extrapolate to higher fluences.

In order to calculate the electrons produced by the x-rays, the Maxwell spectrum was transported through the mylar and the two aluminum shields. This was accomplished by using Quicke2.[13] The spectrum is exponentially attenuated by the code with no scattering. The materials are reasonably thin and of low density so that little scattered radiation contributes to the spectrum. This assumption was checked using FSCATT. The difference was about 2%. The calculated dose on the face of the box was 45.8 Rad(Si). This gives a scaling or renormalization factor of 4.0. A comparison with the TLD data for the dose on the face of the box gives 141.2 for the calculated dose versus 126±23 for the measured dose. The two values are in good agreement.

A prediction for the plane-box short circuit current source is given by

$$I_{sc} \simeq - \frac{10^{-4}}{\Gamma} \, f(t) \, \Delta A \left[(Q_F - Q_{RB}) + (Q_R - Q_{FB}) \right] \text{ (amps)} \qquad (1)$$

where ΔA is the area of the card, Γ is the full width, half-maximum of the pulse, f(t) is the normalized time waveform of the pulse, Q_F is the forward emission from the box wall, Q_R is the reverse emission from the box wall, Q_{FB} is the forward emission from the card, and Q_{RB} is the reverse emission from the card.

Evaluating the above equation for the MMA card yields I_{sc} = 17.2 ma or an equivalent voltage of V= 860 mV into 50 Ω. For the same card shielded from radiation by the aluminum heat shield, the short circuit current is I_{sc} = 5.3 ma or an equivalent voltage of V = 267 mV into 50 Ω. Using the same equation for the generic cards gives short circuit current predictions of I_{sc} = 249 ma or an equivalent voltage of V = 12.5 V into 50 Ω for the uncoated card and I_{sc} = 47.2 ma or an equivalent voltage of V = 2.4 V into 50 Ω for the coated card.

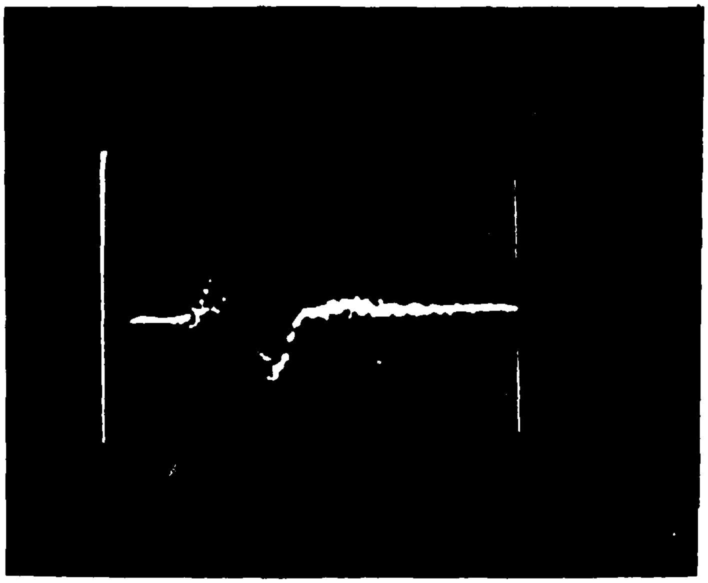
3.1 MARTIN MARIETTA CARD EXPERIMENT

Two Martin Marietta cards (MMA) were placed side by side in the aluminum box and pulsed simultaneously. One of the circuit cards faced the incoming x-ray pulse with its aluminum heat shield behind it. The other had the heat shield facing the beam shielding the card. Data was taken at ambient and vacuum air pressures ($<10^{-3}$ torr). Typical responses of the supply and ground planes are shown in Figures 5 and 6 for ambient and vacuum pressures, respectively. The observed wave forms follow the time history of the driving pulse, suggesting that the x-rays drive the card directly rather than through the electric or magnetic fields. Coupling via electric fields would follow the time derivative of the drive.

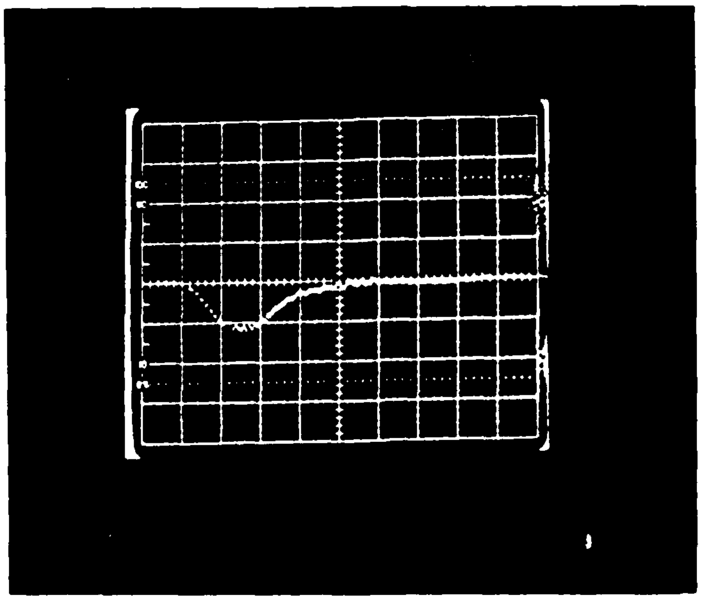
The shots on the MMA card were made with various combinations of biasing, +28v, 0, -28v, and air pressure. These combinations are summarized in Table 1. The results are shown in Figure 7 for both the supply and ground planes of the two cards as a function of shot number. Shot 42 was taken after the card was not used for fourteen hours. The data show several trends; the magnitude of the response is a function of shot number, the card remembers the polarity of

TABLE 1. Summary of pressure and bias voltage for MMA card (MBS SPECTRUM)

SHOT NUMBER	PRESSURE	BIAS VOLTAGE	
		CARD 1 (VOLTS)	CARD 2 (VOLTS)
32	Ambient	0	0
33	Ambient	0	0
34	Ambient	0	0
35	Ambient	+28	-28
36	Ambient	+28	-28
37	Ambient	+28	-28
38	Ambient	-28	+28
39	Ambient	-28	+28
40	Ambient	-28	+28
41	Vacuum	0	0
42	Vacuum	0	0
43	Vacuum	0	0
44	Vacuum	+28	-28
45	Vacuum	+28	-28
46	Vacuum	+28	-28
47	Ambient	+28	-28
48	Ambient	+28	-28
49	Ambient	+28	-28
50	Vacuum	+28	-28
51	Vacuum	+28	-28
52	Vacuum	+28	-28
53	Vacuum	+28	-28
54	Vacuum	+28	-28
55	Vacuum	+28	-28
56	Vacuum	+28	-28
57	Vacuum	+28	-28
58	Vacuum	+28	-28
59	Vacuum	+28	-28
60	Vacuum	+28	-28

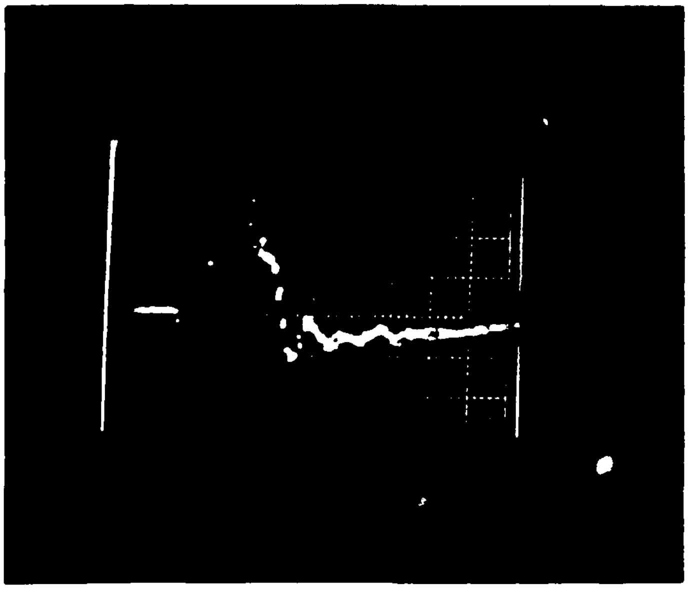


(a) Supply Plane Voltage with Isolation Capacitor in Series
(Scale: 10 mV and 20 ns per division)

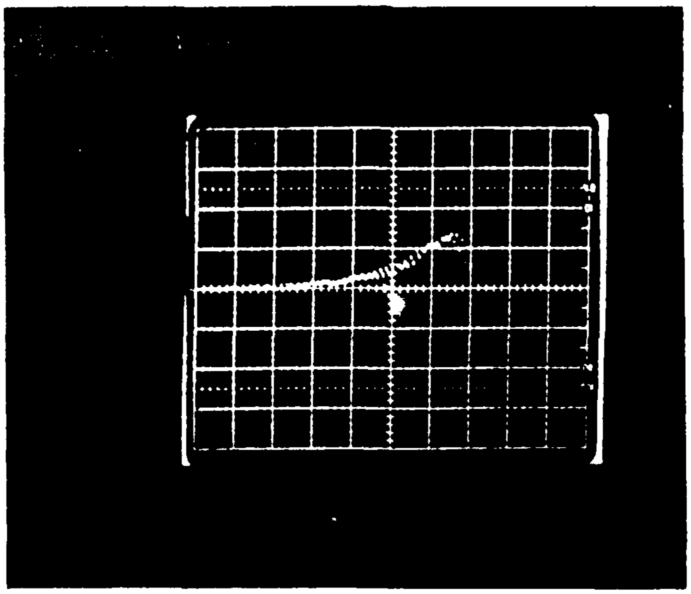


(b) Ground Plane Voltage (Scale: 50 mV and 20 ns per division)

Figure 5. Typical MMA card response for MBS spectrum at ambient pressure with 0 bias voltage



(a) Supply Plane Voltage with Isolation Capacitance in Series
(Scale: 10 mV and 20 ns per division)



(b) Ground Plane Voltage (Scale: 50 mV and 20 ns per division)

Figure 6. Typical MMA card response for MBS spectrum at vacuum pressure and with 0 bias voltage

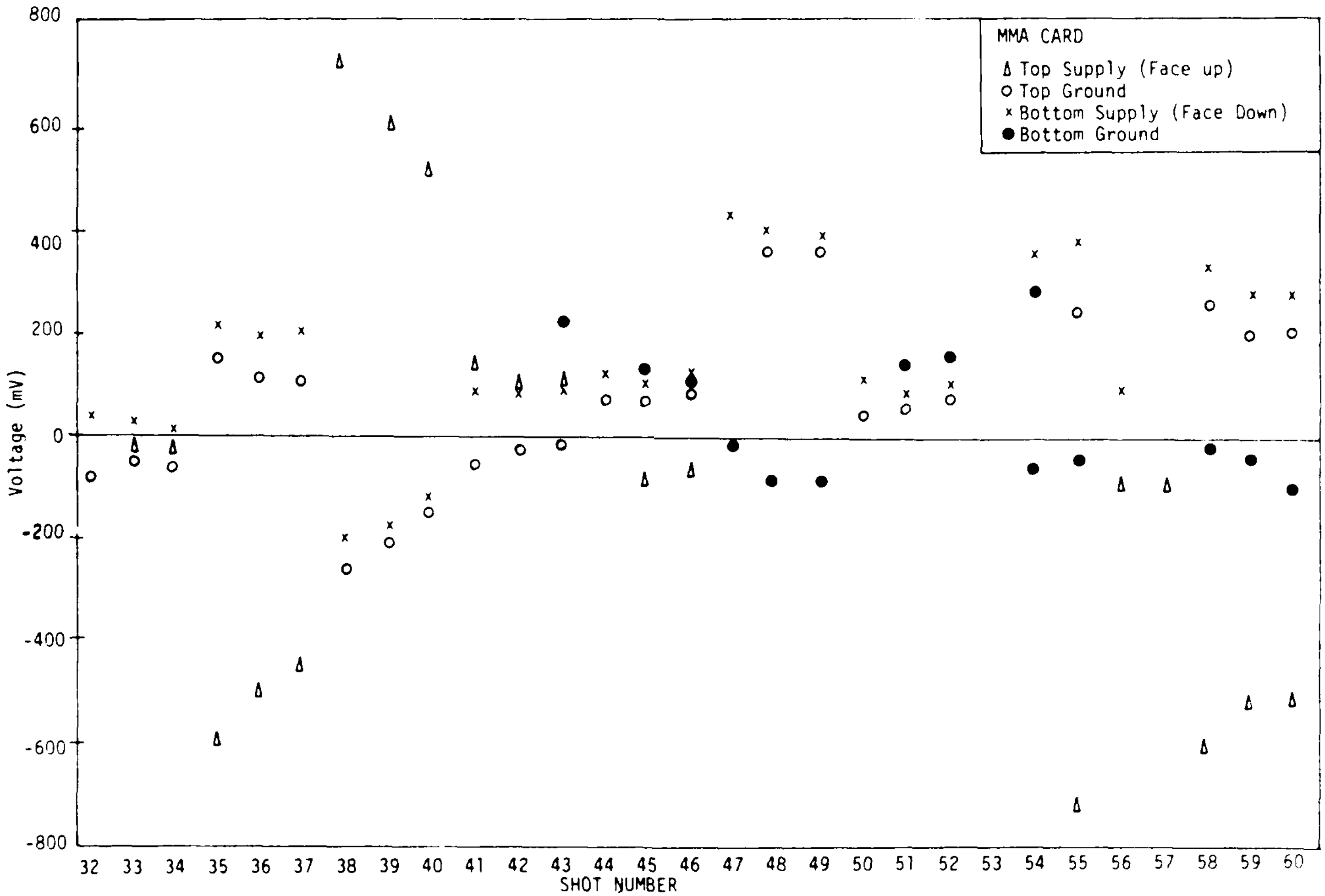


Figure 7. MMA card response for supply and ground planes for spectrum incident on card (top) and spectrum incident (bottom) as a function of shot number

the bias even though the bias is removed, and positive bias results in positive current flowing onto the card from the box. These results are all consistent with the previous experiment.

The predicted value of 860 mV is a factor of three high over the measured value, Shot 41. The response of this card was over predicted in the previous experiment also. The complexity of the multi-layered card may not be adequately modelled. The low measured value shows that the supply plane does not couple strongly to the land plane (Figure 1). The assumption in the calculation was that the two would follow each other. The ground plane-supply plane capacitance effectively shields the supply plane from the response of the land plane.

A comparison between Shots 32-34 and 41-43 gives the difference between the response for ambient and vacuum conditions. In the previous experiment, a large difference was measured but calculations accounted for only a forty (dry air) to twenty (moist air) per cent reduction at ambient pressure due to the shorting out of the fields by the induced conductivity in the air. In this experiment little difference is seen between the two responses. This is in agreement with the prediction.

The effects of positive and negative bias have been explained by the attraction (or repelling) of low energy secondary and conduction electrons causing an enhanced (or reduced) response.[1,2,3] The time dependent response of the cards may be qualitatively explained by the radiation enhanced dielectric conductivity of the card. Trapped charge creates a dipole moment with a time constant of hours or days. This moment results in a lower response for a set of responses taken at a similar time. Even after overnight, the responses may not have returned exactly to "normal" as seen with Shots 32-34 and 41-43.

The measured values of the peak currents induced on the supply plane and ground plane at both ambient and vacuum pressures and for both 0 and +28v biases are extrapolated to higher dose rates in Figure 8. The extrapolation was accomplished by assuming that the induced current is directly proportional to the dose rate, $\dot{D}$.

3.2 GENERIC CARD EXPERIMENT

The same experiment was repeated with a generic card. This simple geometry (Figure 3) was chosen in order to obtain a better understanding of the anomalies observed with the complex card. The same experimental apparatus was used. Card #1 was constructed as shown in Figure 3. Card #2 was the same but was coated with ten mils of carbon (glyptol) to reduce emission from the surface. Typical responses of the supply and ground planes are shown in Figure 9 and 10 for ambient and vacuum pressures, respectively.

Figure 11 presents a summary of the peaks of the responses as a function of shot number where the shot conditions are summarized in Table 2. The prediction for the vacuum response of the card is within a factor of 2 of the measured value. The measured response at vacuum pressures is also a factor of eight higher than the response measured at ambient pressure. This increase is significantly different than for the MMA card. The faces of the generic card are totally covered by copper which results in a factor of four increase in primary electrons. This, in turn, significantly increases the ionization of the air causing the response to be shorted out.

Because of the solid copper faces of the card, the response of the card is driven by the charge transfer between the card and the box. This accounts for the large difference between the ambient and vacuum response. This also minimizes the effects of radiation induced conductivity and trapped radiation effects. The

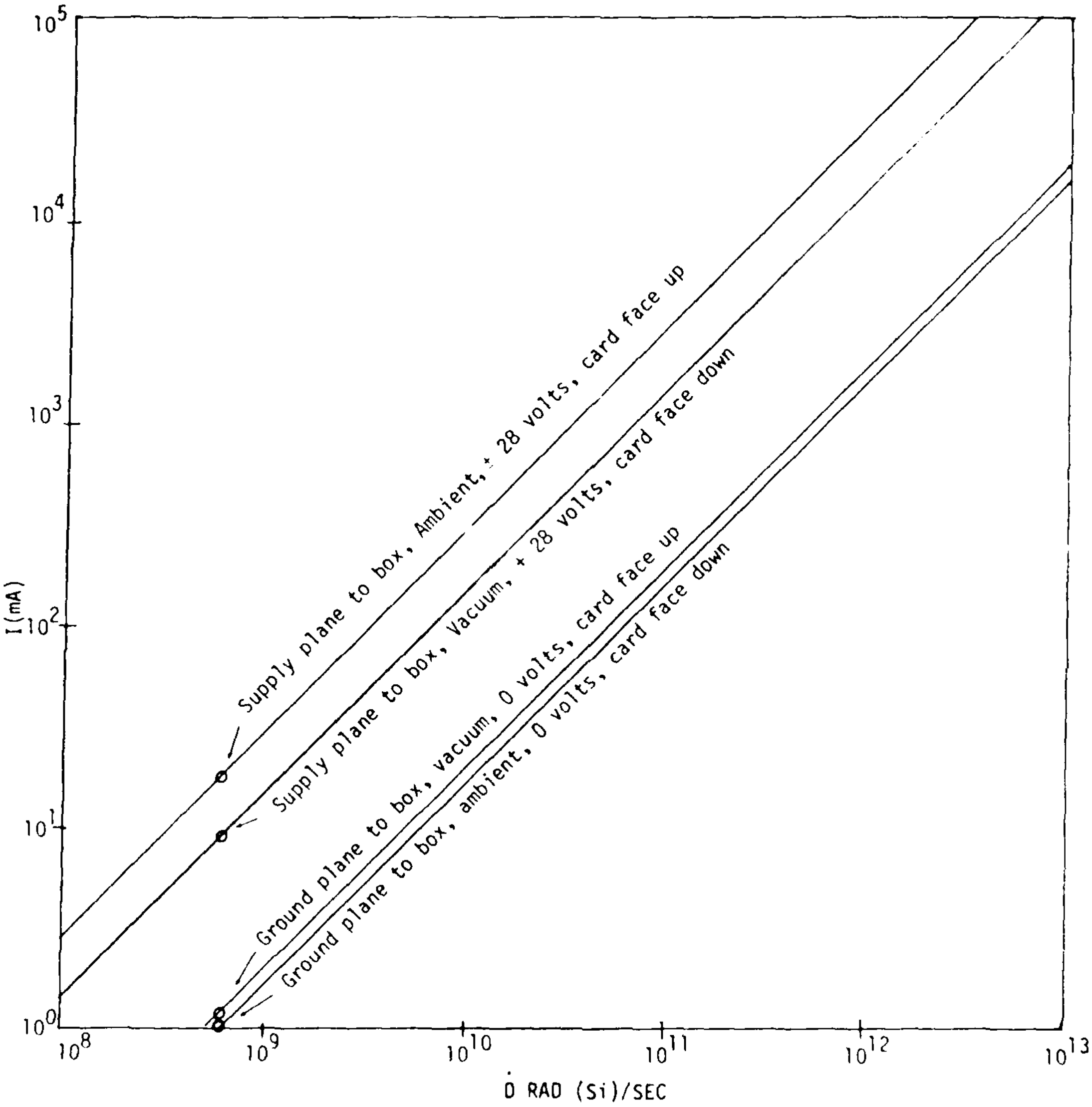
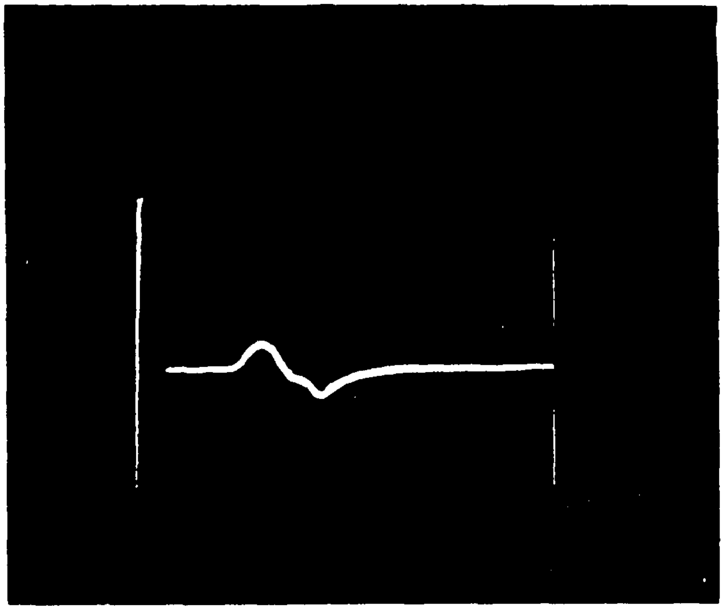
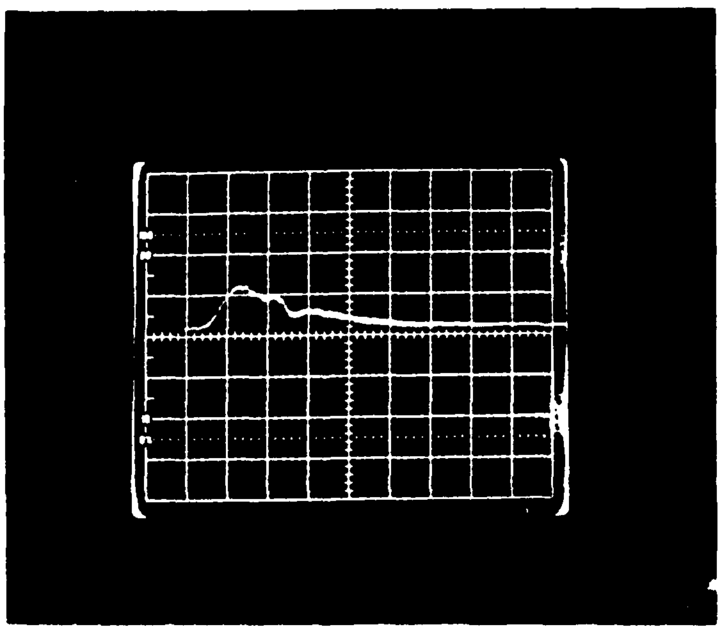


Figure 8. Summary of MBS experimental data for MMA card extrapolated to higher dose rates

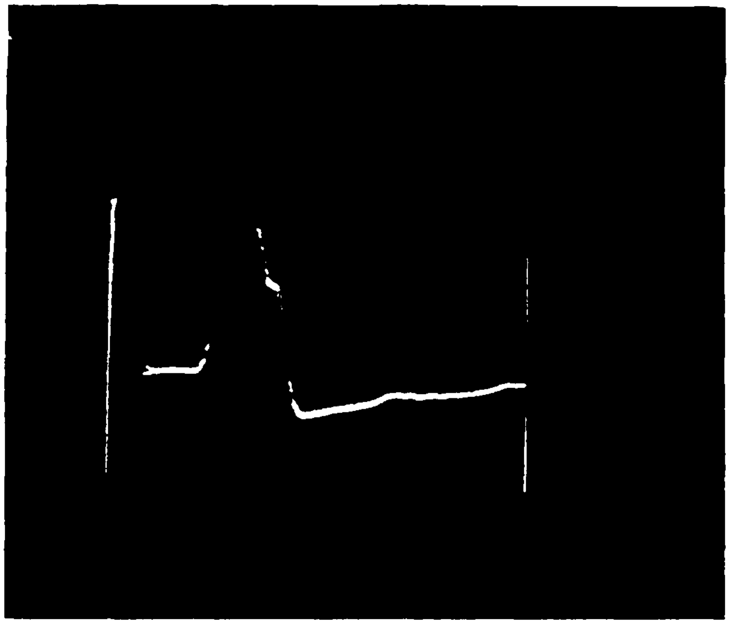


(a) Supply Plane Voltage (Scale: 500 mV and 20 ns per division)

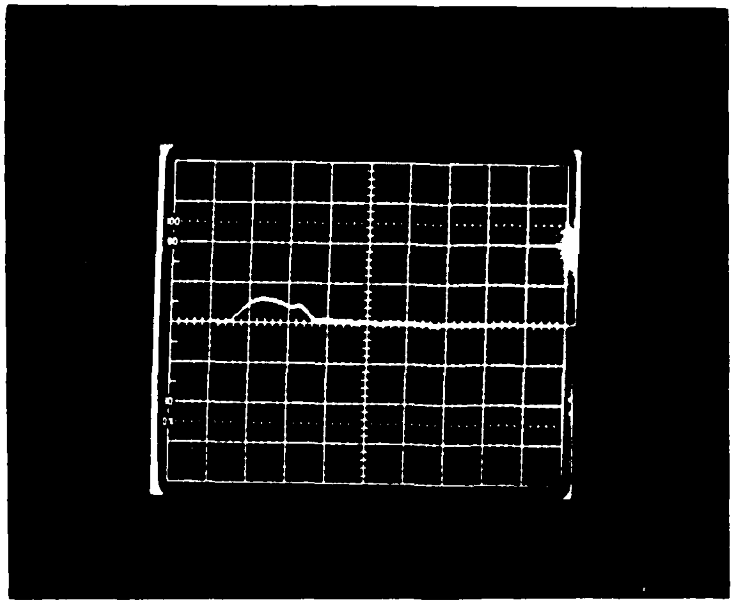


(b) Ground Plane Voltage (Scale: 500 mV and 20 ns per division)

Figure 9. Typical generic card response for the MBS spectrum at ambient pressure and with 0 bias voltage



(a) Supply Plane Voltage (Scale: 500 mV and 20 ns per division)



(b) Ground Plane Voltage (Scale: 5 V and 20 ns per division)

Figure 10. Typical generic card response for the MBS spectrum at vacuum pressure and with 0 bias voltage

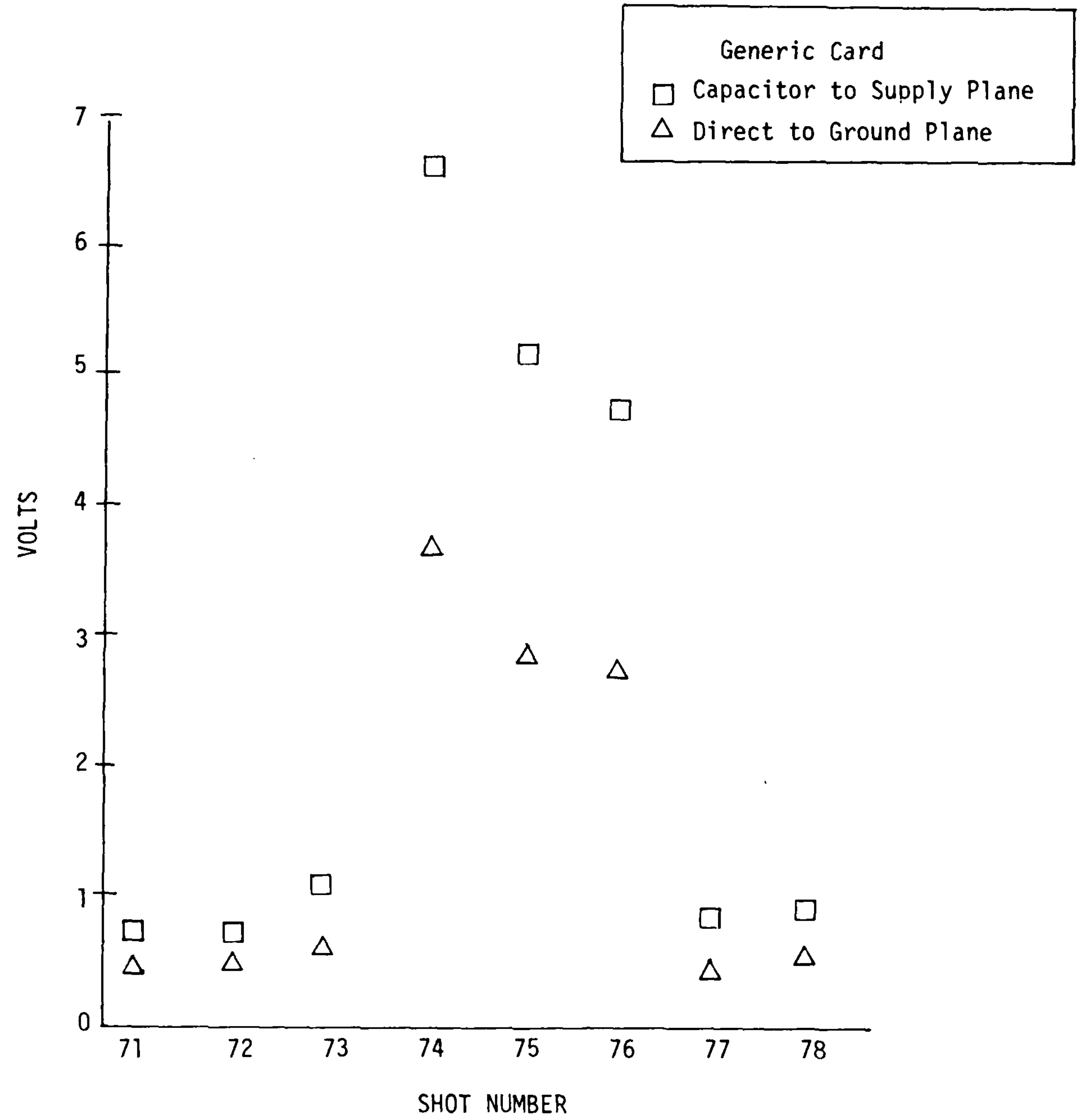


Figure 11a. Measured response of uncoated generic card

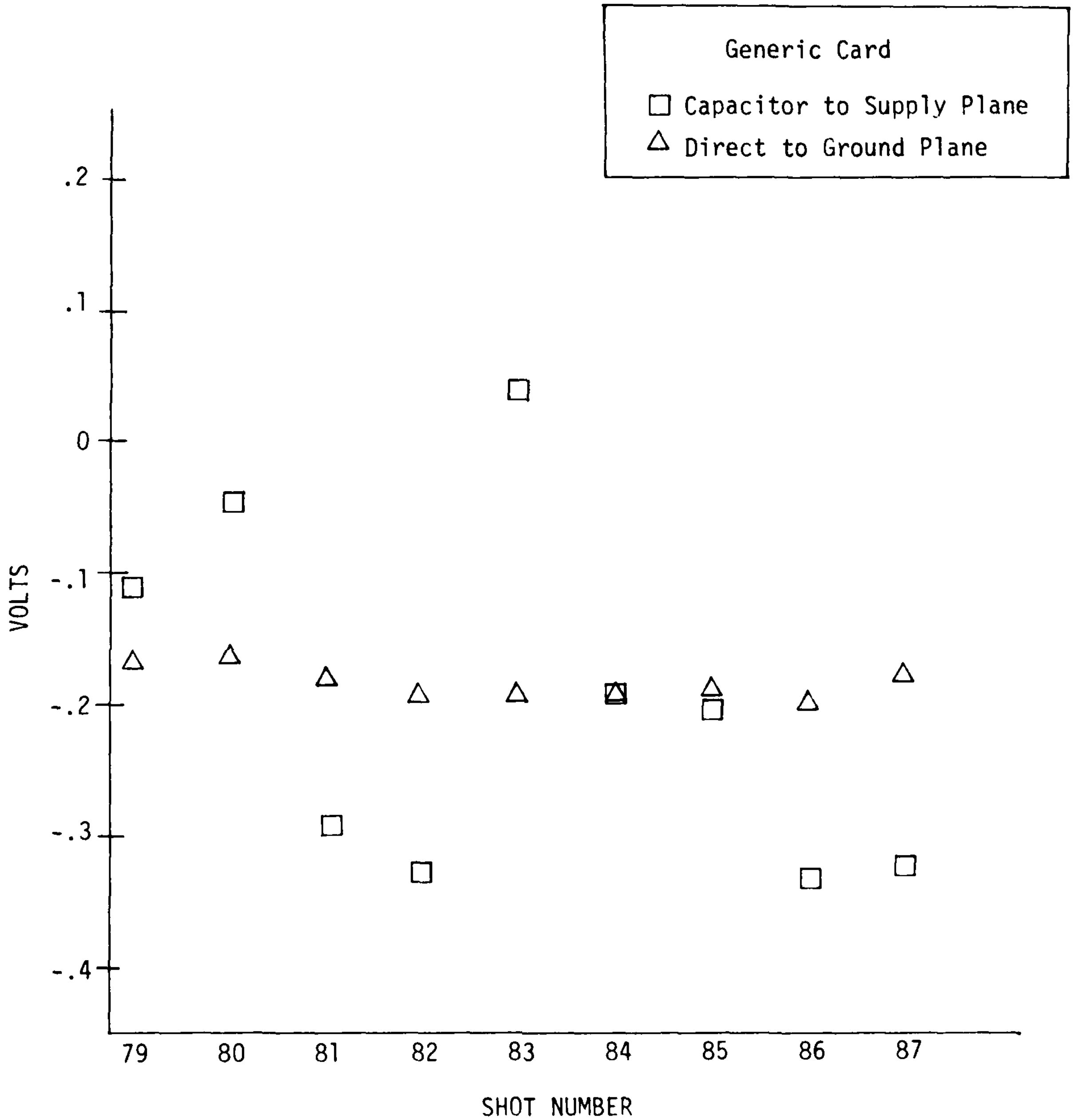


Figure 11b. Measured response of coated generic card

Table 2. Summary of pressure and bias voltage for generic card (MBS SPECTRUM)

CARD NUMBER	SHOT NUMBER	PRESSURE	BIAS VOLTAGE (VOLTS)
1-Uncoated	71	Ambient	0
1-Uncoated	72	Ambient	+28
1-Uncoated	73	Ambient	-28
1-Uncoated	74	Vacuum	0
1-Uncoated	75	Vacuum	-28
1-Uncoated	76	Vacuum	-28
1-Uncoated	77	Ambient	-28
1-Uncoated	78	Ambient	-28
2-Coated	79	Ambient	0
2-Coated	80	Ambient	0
2-Coated	81	Ambient	+28
2-Coated	82	Ambient	+28
2-Coated	83	Ambient	-28
2-Coated	84	Vacuum	+28
2-Coated	85	Vacuum	+28
2-Coated	86	Ambient	+28
2-Coated	87	Ambient	+28

response is not changed a great deal (factors of 2) by biasing the card as it was with the MMA card (factors of 8). The magnitude of the response at one bias and pressure decreases with shot as with the MMA card, but the dependence is less.

The measured values of the peak currents induced on the supply plane and ground plane for 0 bias and at both ambient and vacuum pressures are extrapolated to higher dose rates in Figure 12. Again, the extrapolation was accomplished by assuming that the induced current is directly proportional to the dose rates.

3.3 SUMMARY OF MBS RESULTS

This second test at the MBS facility has successfully duplicated the results of the first test. The response as a function of the time and dose history of the card was again observed. The response of the MMA card under ambient conditions was consistent with prediction. The results did not appreciably differ from those in a vacuum.

The response of the generic card was predicted within a factor of two using Equation (1). However, the response was greatly over predicted for the complicated MMA card. The simple analysis does not correctly model the response of more sophisticated geometrics where multiple planes can decouple the response of the internal planes from the box to card driver.

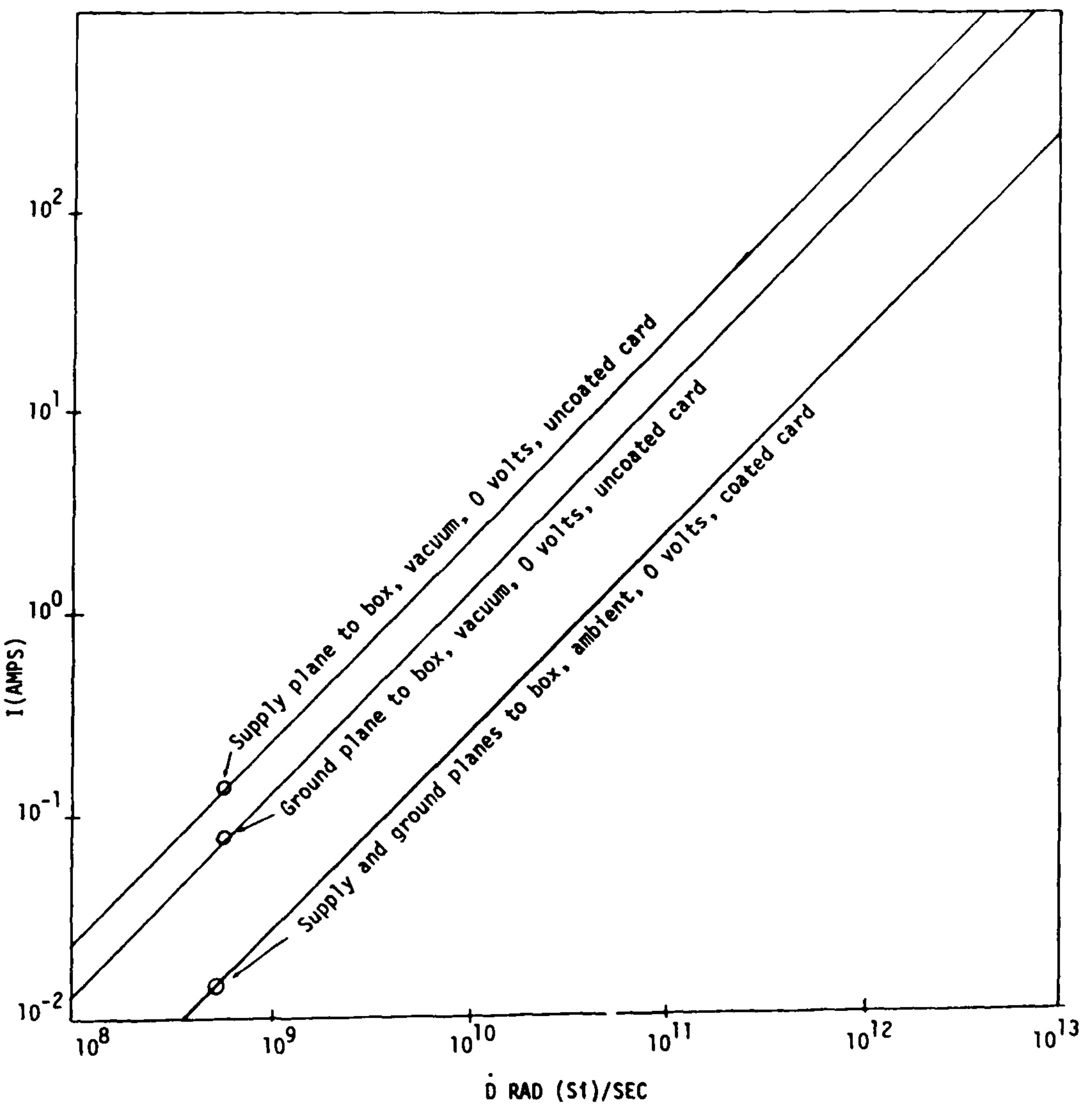


Figure 12. Summary of MBS experimental data for generic card extrapolated to higher dose rates

SECTION 4

BJ3 EXPERIMENTAL CONFIGURATION

In order to investigate the response characteristics of the circuit cards exposed to high fluences, an experiment similar to the one using the MBS spectrum was performed at the BJ3 facility of Maxwell Laboratories. This facility provided a higher dose rate of about 3.0×10^{11} Rad(Si)/sec with an average photon energy of $\langle E \rangle \sim 120$ KeV. This is compared with 7.0×10^{9} Rad(Si)/sec and $\langle E \rangle \sim 25$ Kev. Those dose rates were measured at the outer surface of the aluminum that housed the experiment.

The experiment was housed in an aluminum box to provide shielding from the BJ3 electromagnetic environment. Semi-rigid coaxial cable was used to connect the aluminum box to the screen room. All of the coaxial cable was housed in a flexible metal pipe that provided additional shielding. The RF pickup appearing as noise was negligible.

The x-ray spectra was filtered by eight layers of material. Six of the layers were Grafoil, each 15 mils thick, and one layer of Kevlar, 140 mils thick, were used to attenuate electrons and debris from the tantalum converter. The eighth layer was provided by the aluminum box cover which was 62.5 mils thick. Figure 13 gives the BJ3 spectrum before and after it interacts with the aluminum cover.

The energy spectra were scaled to TLD dose measurements taken with each shot. All the shots were normalized to 4.2×10^{11} Rad(Si)/sec. The measurements had a spread of 2.1×10^{11} to 4.2×10^{11} Rad(Si)/sec. The average dose was 3.5×10^{11} Rad(Si)/sec. These doses represent an average of three measurements made over

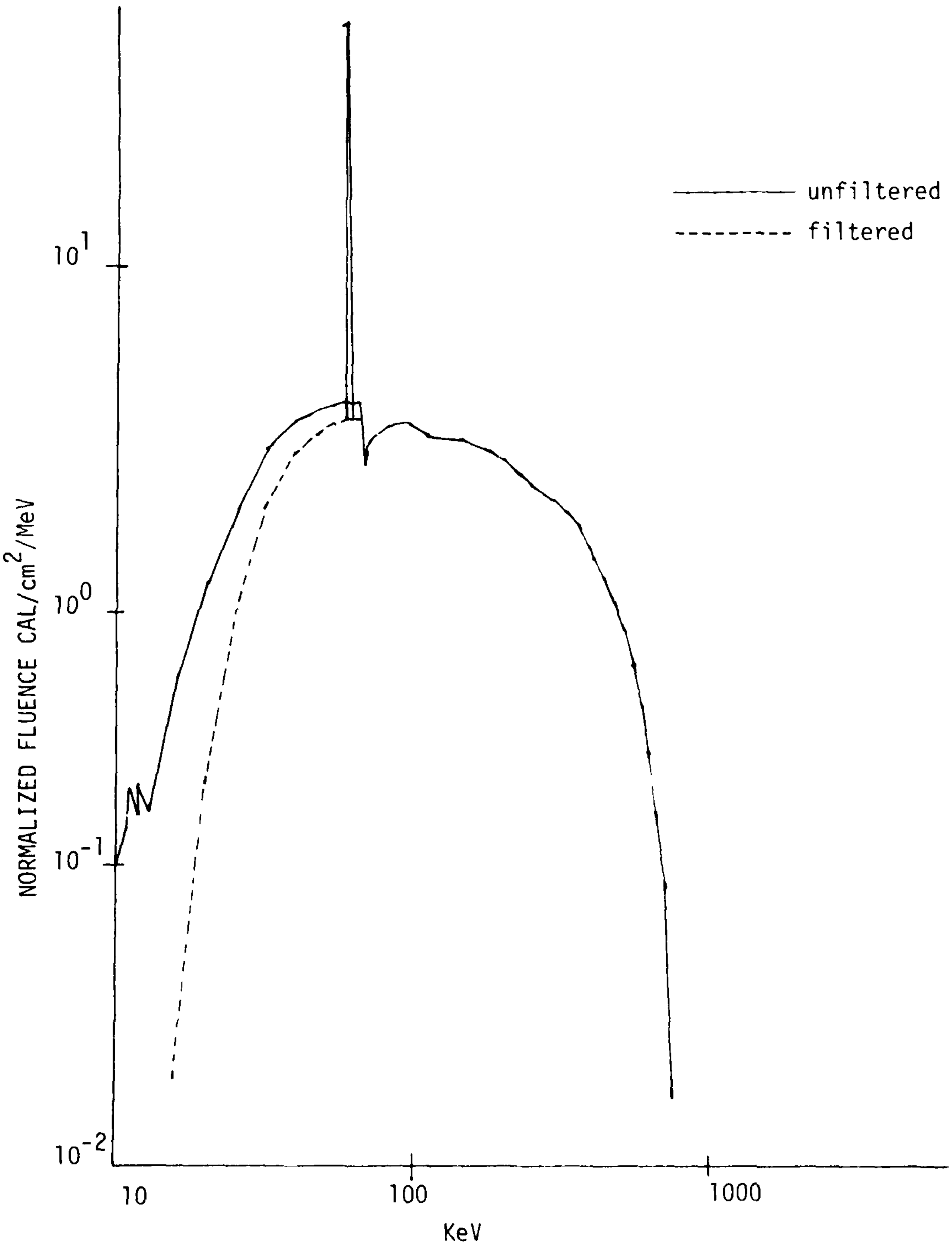


Figure 13. BJ3 x-ray spectra incident on box and circuit boards

the face of the card. The doses varied less than 3 percent over the face of the card.

The same cards were used as in the previous experiment with the MBS spectrum. The generic card was divided in half and one half was coated with Kapton (30 mils) to suppress electron emission. Both halves were placed side by side and pulsed simultaneously.

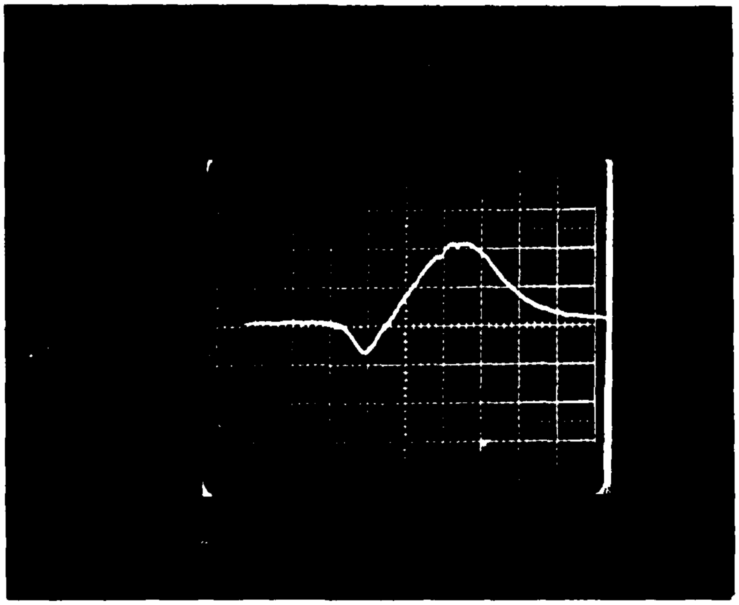
4.1 MMA CARD EXPERIMENT

A typical MMA card response for the BJ3 spectrum at ambient pressure and with a bias voltage is shown in Figure 14. The wave forms show that the response of the card follows the direct charge transfer between the box and the card.

The peak amplitude of the measured voltages for the MMA card as a function of shot number is presented in Figure 15 for the BJ3 spectrum. For shot numbers 7, 12, and 13, the ground plane voltage exhibited a bi-polar response. The magnitude of each peak is shown in Figure 15. The pressure and bias voltage for each shot is summarized in Table 3.

Table 3. Summary of pressure and bias voltage for MMA card (BJ3 SPECTRUM)

SHOT NUMBER	PRESSURE	BIAS VOLTAGE (VOLTS)
5	Ambient	0
6	Ambient	+28
7	Vacuum	+28
8	Ambient	+28
9	Ambient	-28
10	Vacuum	-28
11	Ambient	-28
12	Ambient	0
13	Ambient	0



(a) Supply Plane Voltage (Scale: 2V and 20 ns per division)

(b) Group Plane Voltage (Scale: 2V and 20 ns per division)

Figure 14. Typical MMA card response for the BJ3 spectrum at ambient pressure and with 0 bias voltage

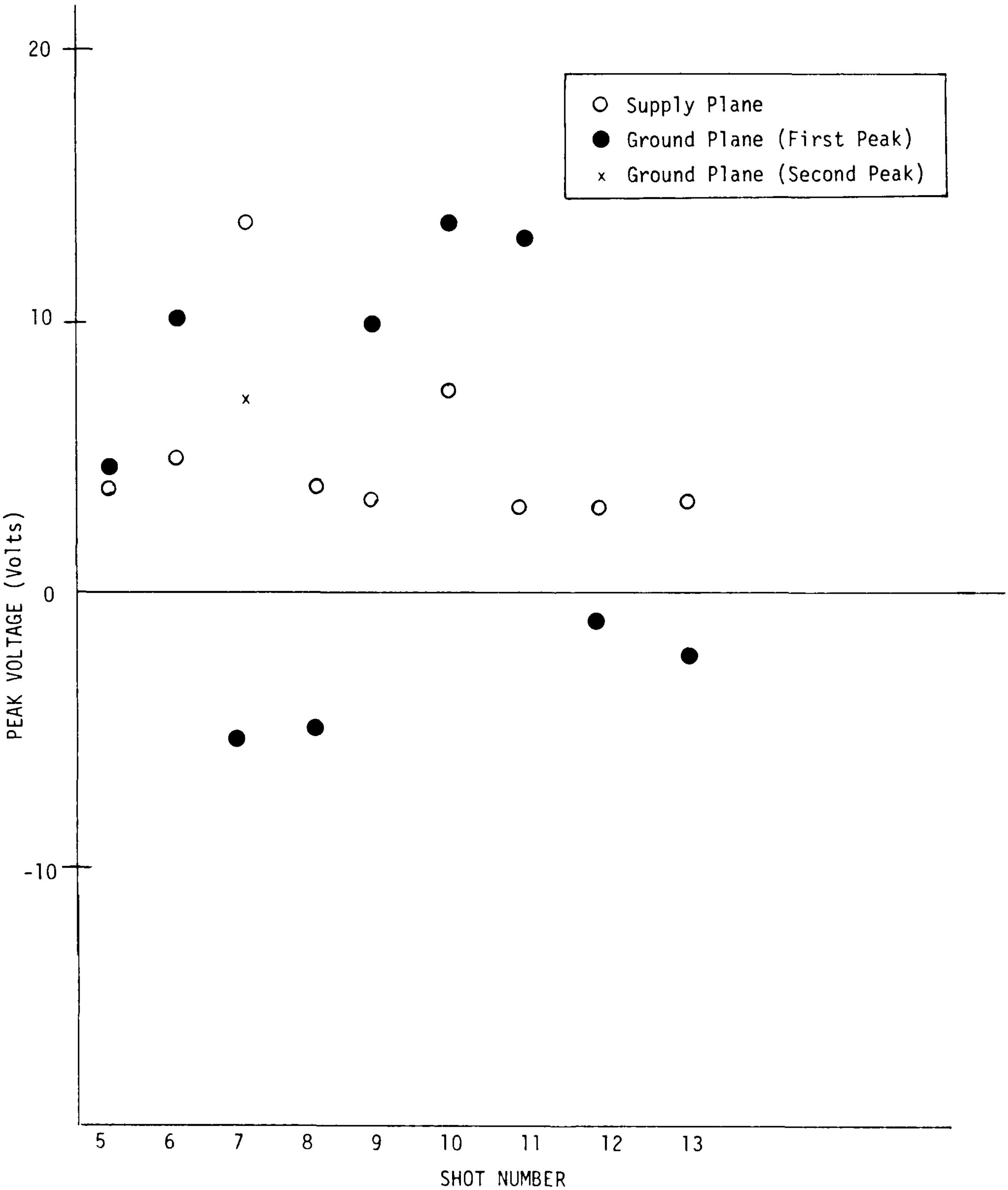


Figure 15. MMA card BJ3 response for supply and ground plane as a function of shot number

A prediction for the supply plane response at ambient pressure can be made by extrapolating the MBS pulse to the BJ3 dose. The BJ3 dose is 43 times the MBS. From Figure 8, the extrapolated response for the supply plane at ambient pressure and 0 bias voltage is 40 ma or 2 volts. The measured value is 4 volts. This result is consistent with the MBS spectrum having more energy in the 20-70 KeV range.

An analytic prediction can be made using the Equation 1. The predicted voltage for the MMA card is 23 volts. No direct measurement of the card under vacuum/no bias conditions was made. From the measurements, however, the response does not change a great deal with bias under ambient conditions. This result is consistent with the premise that the card response is driven by the box-card currents rather than by the induced currents within the card. In Figure 16, the measured responses of the MMA card for the BJ3 spectrum are extrapolated to threat; again it was assumed that the card response is directly proportional to dose rate.

4.2 GENERIC CARD EXPERIMENT

Typical results for the response of the generic card to the BJ3 spectrum are shown in Figures 17 and 18 for ambient and vacuum pressures respectively. The plot of peak voltage versus shot is shown in Figure 19 for the supply alone. The shot conditions are summarized in Table 4. Again, the response is dominated by the currents flowing between the card and the box. The ambient response as a function of bias voltage does not change significantly between shots. The vacuum response is a factor of three higher than the ambient. This response is dominated by the large electron current between the copper card and the box.

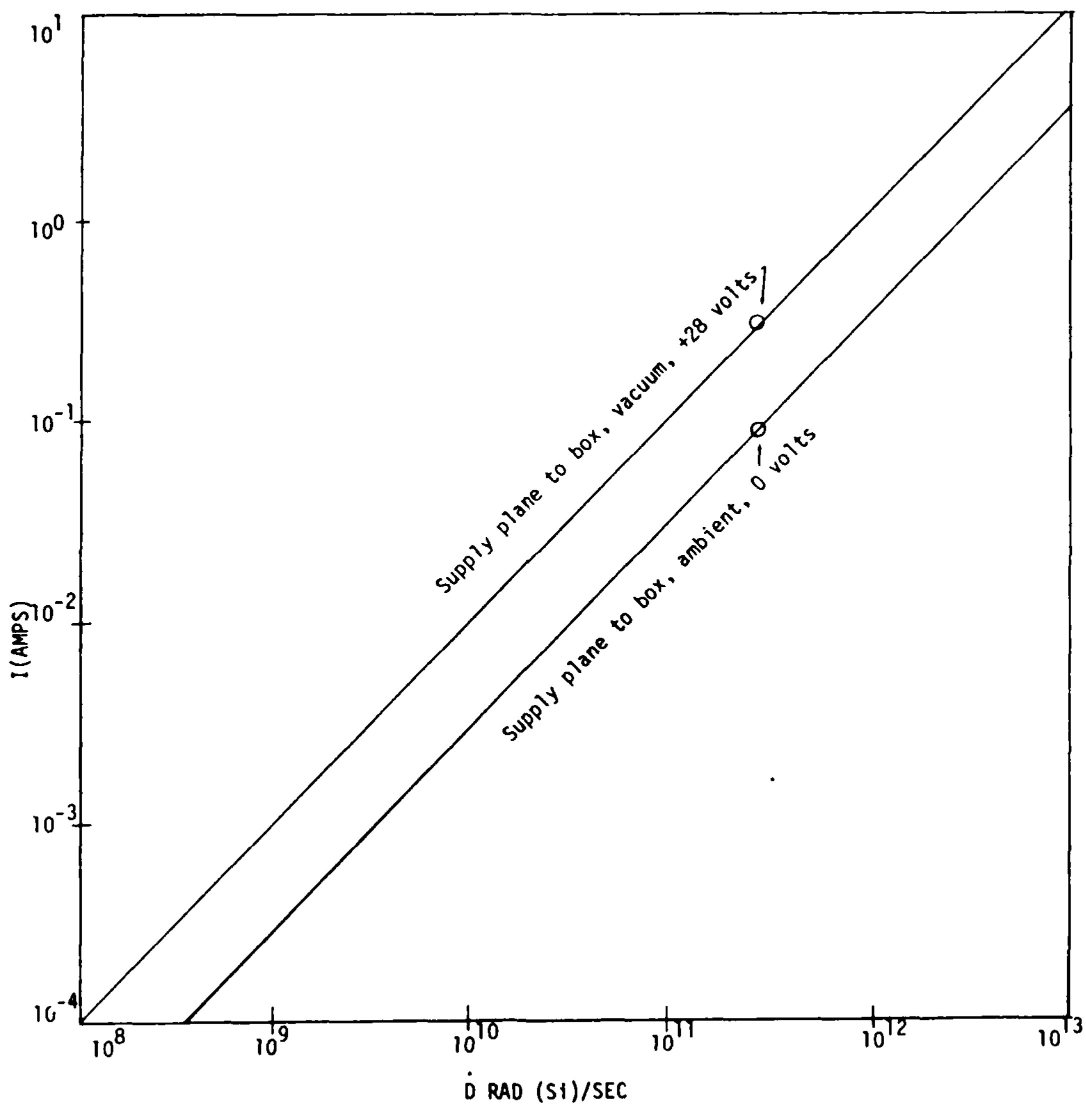
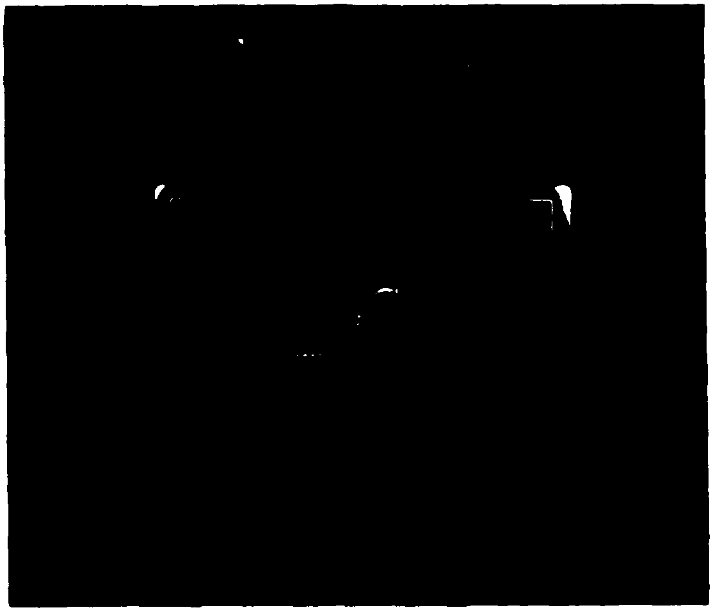
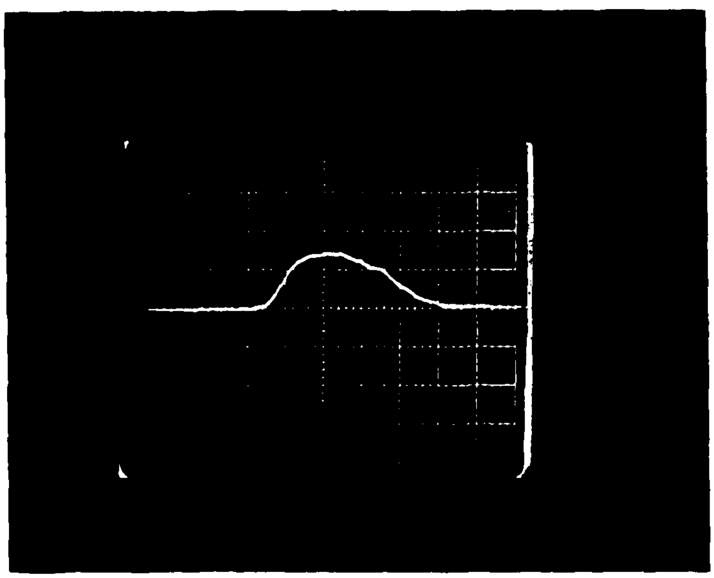


Figure 16. Summary of BJ3 experimental data for MMA card extrapolated to higher dose rates

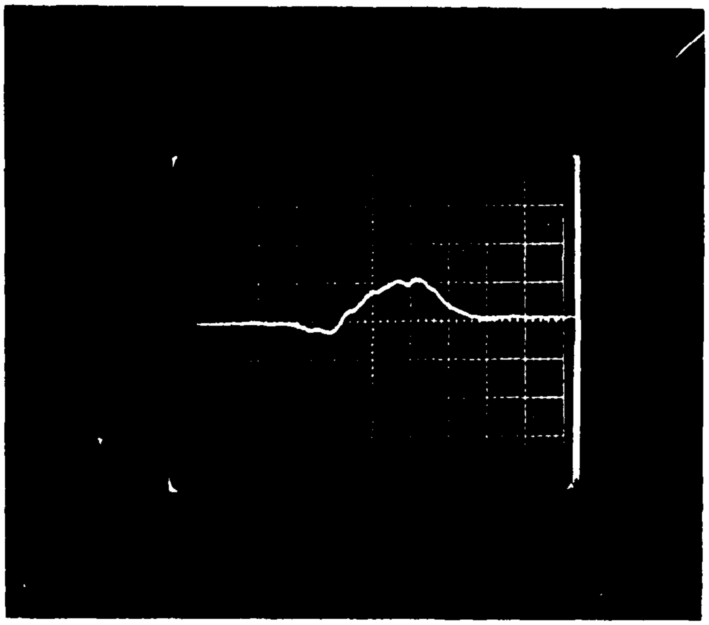


(a) Supply Plane Voltage (Scale: 5 V and 20 ns per division)

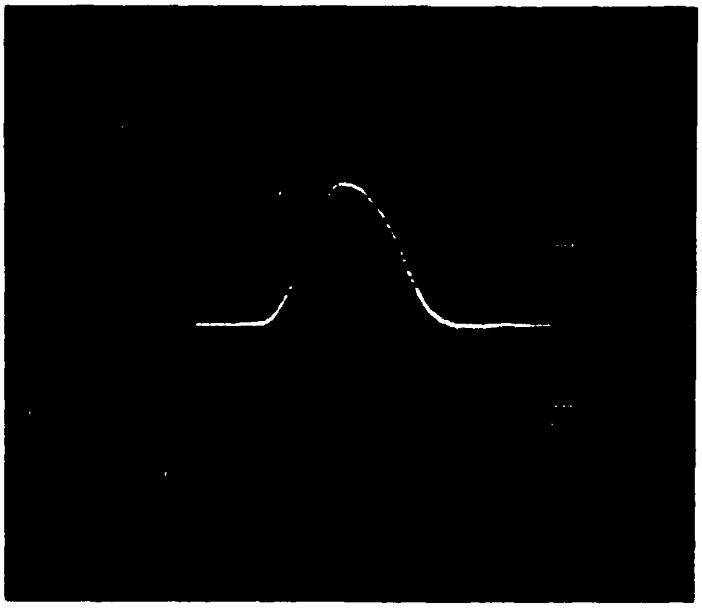


(b) Ground Plane Voltage (Scale: 5 V and 20 ns per division)

Figure 17. Typical generic card response for the BJ3 spectrum at ambient pressure and with 0 bias voltage



(a) Supply Plane Voltage (Scale: 5 V and 20 ns per division)



(b) Ground Plane Voltage (Scale: 2 V and 20 ns per division)

Figure 18. Typical generic card repsonse for the BJ3 spectrum at vacuum pressure and with 0 bias voltage

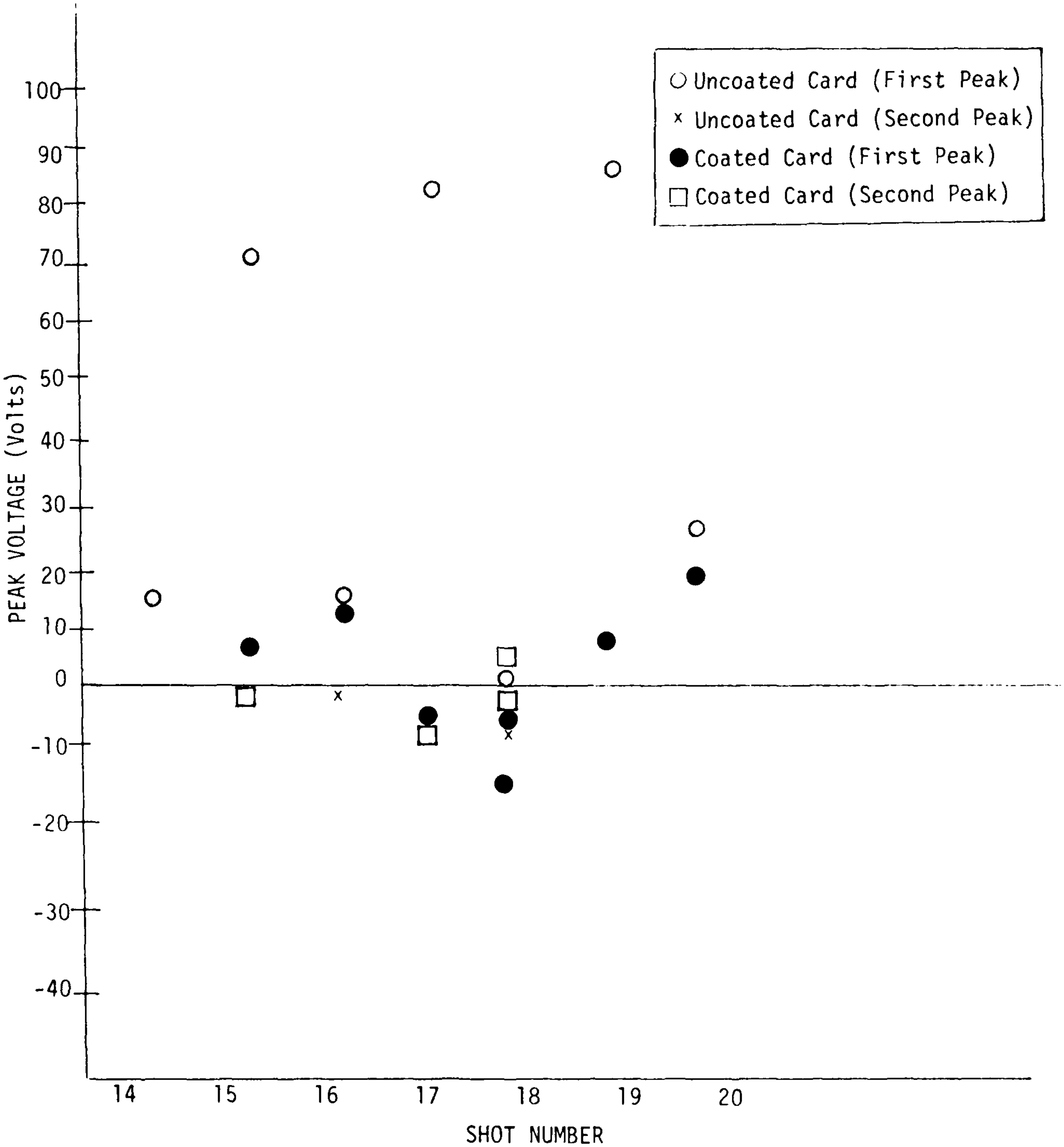


Figure 19. Generic card BJ3 response for both coated and uncoated cards as a function of shot number

Table 4. Summary of pressure and bias voltage for generic card (BJ3 SPECTRUM)

SHOT NUMBER	PRESSURE	BIAS VOLTAGE (VOLTS)
14	Ambient	0
15	Vacuum	0
16	Ambient	0
17	Vacuum	+28
18	Ambient	+28
19	Vacuum	-28
20	Ambient	-28

The predictions for the vacuum response for these cards using Equation 1 are 55 and 119 volts for the coated and uncoated cards, respectively. These results are within sixty percent for the uncoated card but a factor of nine high for the coated card.

An interesting characteristic of the responses under ambient conditions is that the responses of the two cards are the same. Both follow the primary electron current. The secondary electrons in the air shorting out the response produces the same reduction in current flowing onto each card. The response of the coated card is similar under vacuum and ambient conditions. In Figure 20, the measured response of the uncoated generic card for the BJ3 spectrum is extrapolated to threat; again, it was assumed that the card response is directly proportional to dose rate.

4.3 SUMMARY OF BJ3 TEST

The most significant result of this test is that scaling to higher fluence levels is accurate at least for the spectrum and doses of the two facilities used at Maxwell Laboratories. No new non-linealities or anomalies were observed. The responses of the

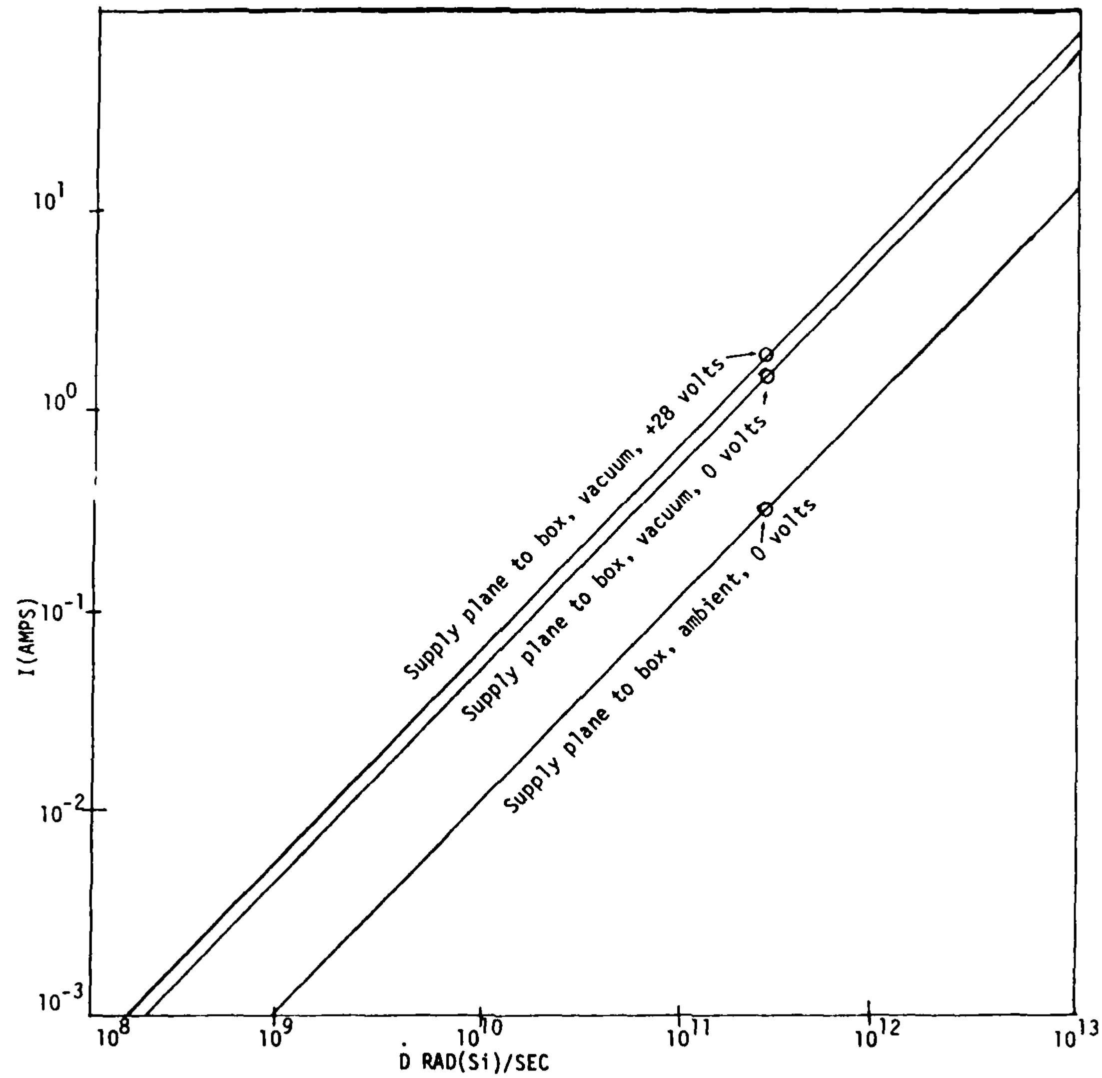


Figure 20. Summary of BJ3 experimental data for generic card extrapolation to higher dose rates

cards were dominated by the box to card currents. The effects of dipole layer formation and charge buildup were much less significant for the BJ3 spectrum than for the MBS spectrum and dose rate.

SECTION 5
CONCLUSIONS AND ISSUES

Extrapolations need to be made from the response of blank multi-layer generic cards to those with components of real hardware. In these tests, card response has been defined as the currents flowing on or off ground or supply planes. Applying the results of these tests to actual cards can be accomplished in a bounding manner. One extreme would be to put all of the current onto one land of a device. For this comparison, the results of the BJ3 test with the generic card under vacuum and no bias are used. These curves are shown in Figure 19.[8] A lower bound would be the second set of curves on the same figure which represent the current from 1 cm^2 of land. For the unhardened 60 cm^2 board, components begin to fail at 10^{11} Rad(Si)/sec. This is conservative because most devices are biased. At the present, the amount of current that will attach to a particular land is not known. The approach suggested here is to use the larger value until such time that the current coupling from land to device is better understood. The mechanism of this coupling should be examined in a future program.

Figure 8 shows, in part, the response of the plane that is next to the aluminum heat shield (Figure 1). The response here approximates the plane to plane response of a multi-layered card. For both ambient and vacuum unbiased conditions, about a 70 mV or 1.4 ma transient was seen. This current would pass from plane to plane via components that connect the planes.

Many of the components that connect circuit cards to boxes or connect planes of cards are either hardened or are constructed robust enough to survive the transients described here and elsewhere. Examples include IC already hardened for TRE effects, clipping diodes and series limiting resistors. Noting the existence of each component, the technology exists for hardening boards to many aspects of these IEMP transients. What is unknown is how standard are these practices used in designing circuit boards? A future program should look at this issue.

The induced conductivity of the air under ambient conditions limits the response of the cards by shorting out the induced voltage. The magnitude of this effect has been adequately predicted for the MMA card and noted previously.[3,5] For the generic card (the total face covered with copper) the response is under predicted. The response is under predicted by a factor of five for BJ3 spectrum and a factor of eight for the MBS. In addition, the time history is not adequately modelled. The bipolar pulse shown on Figure 6 is not predicted by the analytical model. This issue should be examined in future efforts.

In the first test with the MBS spectrum for the MMA card, the response was over predicted. The simple formulation (Ref. 5, 8) for generic like cards did not adequately model the response of a complex multi-layered card. Results from this report and the previous references have shown that for simple cards, the responses can be adequately modeled. Efforts should be applied to understand the response of circuit cards that are currently being fielded in electronic systems.

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